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GEOMETRY AND LEANING OF ALHADBA MINARET

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ABSTRACT

There is great effort of planning to rebuild the recently destructed Alhadba minaret in Mosul. A major requirement is to study the original shape and materials. During the past years, there was a considerable amount of leaning in the minaret due to various natural and human causes. The amount of leaning was generally increasing, but there was no unified or fixed control that is referenced from various monitoring groups. This paper describes the effort that was performed to design and implement a monitoring system that can be referred. Fixed control points and targets have been worked. Samples of monitoring results are presented. Data can be used for reconstruction.

KEYWORDS: Mosul Alhadba Minaret, Leaning Monitoring & Heritage Preservation

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Original Article

INTRODUCTION

The legend of Mosul city is Alhadba (the leaning) minaret. It is one of the oldest Islamic monuments in Iraq dated back to 1172 AD. Its location forms a focus in the older part of the Mosul city on the right side of river Tigris. Researchers study this monument for many interesting reasons some are listed below.

- Peculiar leaning of the minaret.
- Noticeable height (50 m) and age as compared to the nearby old city housings. figure 1.
- Resistance to centuries of deterioration due to weather, quakes, and human disturbance around the minaret.
- Documentation of cultural heritage.
- Preparation for restoration, maintenance, protection and safety.

The minaret has undergone maintenance operations at various stages of its life and probably the most obvious was that conducted by Fondedile S.p.A. company in the 1980s [1] which was performed to strengthen the body of the minaret as well as the foundation and the surrounding soil.

During the past decades, there were studies and tests to examine its construction materials, the carrying soil, foundations and record measurements in and around the minaret [2,3,4]. Of particular interest here is the direction and amount of leaning that have to be monitored accurately and systematically. Recorded surveying measurements of the amounts of leaning dated back to the sixties (1964). Reports at that period refer to leaning at various elevations on the surface of the minaret body. Unfortunately, the reference controls and the monitoring marks were not well documented. Later on, more monitoring operations were conducted for comparisons. Again

there, new references of measurements were not maintained. Leaning of the minaret was caused by many reasons. Ali [5] suggested that the wind pressure was the cause of that leaning. Other reasons are related to the underground foundation and soil [1].

Figure 1: Alhadba, a Focus Area within the Old City of Mosul Before and After Destruction

Recently, the minaret was almost destroyed by war operations in Mosul. Accordingly, there is an effort to rebuild the minaret and develop the area in the nearby vicinity. A major requirement is to collect and analyze the past documentations of geometry and leaning. In this paper, the authors present their work performed during the years 2010 to 2016 to design a surveying and monitoring program and record the first results obtained. Most of measurements collected were based on the use of total station with reflectorless capability to measure the hard to reach and vulnerable locations around the trunk of the minaret. This work documents the techniques used for measurements and presents samples of results.

BACKGROUND AND INSTRUMENTATION

Monitoring the deformation and leaning of heritage and high rise structures is necessary during the life time of buildings to assess safety and maintenance works [6]. In literature, there are many monitoring techniques that differ in many aspects such as cost, speed, precision and expert requirements. Well known methods are based on triangulation, GPS, Photogrammetry, Laser scanning and others [7,8]. Total station triangulation and trilateration methods use the high precision distance and angle measurements to produce 3D location of target points [9]. In this research, the authors use Topcon Imaging Station IS-203 (a variant of robotic total station). This instrument have least readings of 0.2 mm in distance and 1˝ in angle measurements see figure 2. In its reflectorless or (non-prism (NP) mode), this machine can measure up to 350 m distances. IS-203 is driven by the onboard TOPSURV surveying software that can use various functions to increase measuring productivity. In prism mode, the fine distance accuracy reaches ±(2mm + 2ppm X Distance) mse. While in non-prism mode the accuracy amounts to ±(5mm) mse. Angular accuracy is 3˝.[10]

The instrument can be operated in the reflectorless automatic scanning mode to produce point cloud of targets in three dimensions.

Necessary corrections and calculations of measured distances are worked internally by the instrument after feeding in basic input data and air pressure and temperature[10,11,12,13].

For precise elevation measurements, Topcon digital level with precision of 0.2 mm reading was used for fixing elevations of a set of control points around the minaret.

Figure 2: Topcon Imaging Station at Monitoring Work

NETWORK OF CONTROL POINTS

In order to monitor deformation of an object, it is required first to locate a set of fixed control points. In this work, the ground control set of points have been selected considering the following limitations.

- Control points must be far away from the minaret body to be out of any possible soil subsidence effects caused by the minaret. In the mean time, far locations may reduce accuracy of measurements.
- Building materials of most nearby housings is not rigid enough to fix permanent control points on the roofs. Old houses are made of stone and gypsum.
- Points must be far from nearby human disturbance knowing that the mosque is frequently crowded and situated near the center of the city.
- Old city subsoil is generally composed of few meters of old ruins with cavities and loose compaction regarded as non stable.

Taking all mentioned limitations into consideration we have only few suitable locations to fix (good) points. we have selected the set of 10 control points shown in figure 3.

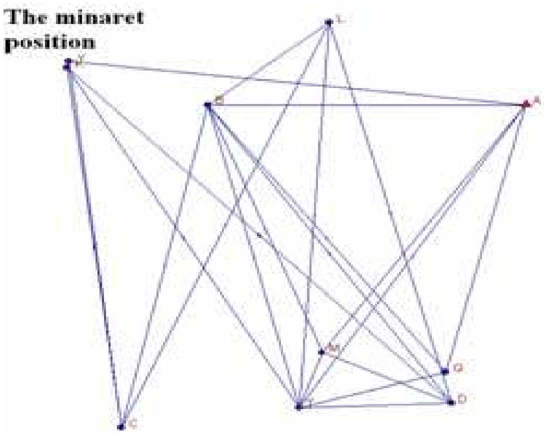

Figure 3: Network of Control Points. (East to the Right)

Unfortunately, not all control points are intervisible. Point (A), is the major control point fixed into the garden at about 70 m from the minaret base. It is a concrete box about 1m side with steel mark. It approximately faces the eastern convex side of the leaning body along the leaning direction. Most of control points in figure 3 are not proposed for actual

monitoring in the future. They are adopted only at this early stage in order to strengthen the network configuration and increase precision of coordinate measurements using least squares solutions. Some of these control points can not be used for setting up surveying instruments. They are used for orientation during setting up. Points D and Q are fixed on the (rigid) concrete roof slab of the mosque. They are stable and face clearly key target points on the trunk of the minaret. Using epoxy adhesive at each point, a steel bolt is fixed into a small hole drilled into the concrete roof. The bolt head has been treated against corrosion and a small point has been marked in the center of the head for precise referencing of surveying instruments.

Coordinates of control points have been calculated after collecting angular and distance measurements to all visible points using the total station in prism measuring mode. All angles and distances have been measured many times and averaged to obtain most probable values. Least squares 2D network adjustment have been carried out to find coordinates of points. All coordinates are local. The following table shows the achievable accuracy level. The solution passed the Chi squared test.

Table 1: Adjustment Results of the Control Network

Adjustment Statistical Summary

Convergence Iterations	= 3
Number of Stations	= 10
Number of Observations	= 28
Number of Unknowns	= 18
Number of Redundant Obs	= 10

Observation	Count	Sum Squares of StdRes	Error Factor
Angles	21	0.961	0.358
Distances	6	4.634	1.471
Az/Bearings	1	0.000	0.000
Total	28	5.596	0.748

The Chi-Square Test at 5.00% Level Passed
Lower/Upper Bounds (0.570/1.431)

FIXING OF MONITORING TARGETS

Targets are made of steel bolts of 2 cm head diameter worked using turning machine. The head was rounded and a small hole mark of 1 mm diameter was drilled in the head center representing the exact monitored mark. Bolts are white painted. See figure 4. A high crane was used in fixing these targets and great care was taken in order not to hit the minaret surface or make any destruction as seen in figure 5. A bore hole of about 4 cm deep was drilled into the wall of the minaret, cleaned with brush and filled with adhesive. Finally, the steel bolt pressed into place.

Bolts have been fixed in key locations along the total height of the minaret. Their positions are facing East where the set of control points can be visible from more than one monitoring location.

Figure 4: Steel Bolts Prepared as Targets

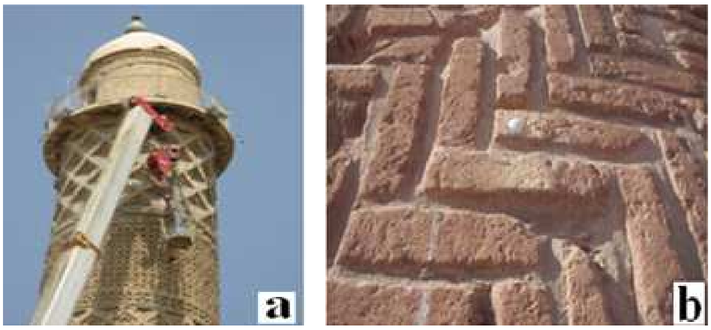

Figure 5: a) Fixing Target Points b) Target Point Ready for Monitoring

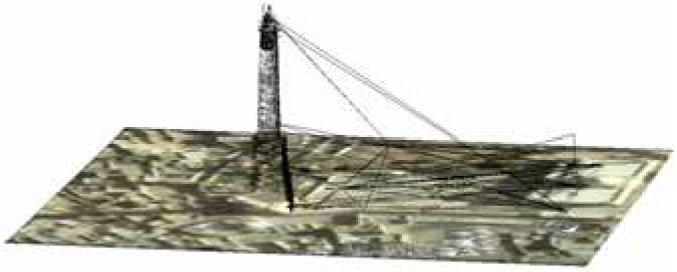

Figure 6: 3D View of Monitoring Lines of Sight Superimposed on Google Earth Image of the Nearby Area.

MEASUREMENTS AND RESULTS

All distance measurements have been made using prism and non prism modes of the total station. Moreover, scanning results in the form of point clouds have been analyzed. During the past few years, results of deformation monitoring on selected points on the prismatic base of the minaret does not show significant side movement. However, the point cloud obtained in this study shows that the two western and eastern faces of the base are not symmetrical as seen in figure 7. A possible differential tilt of the minaret base of about 2 degrees eastwards have occurred after construction. The eastern side wall of the prismatic base is currently out of vertical by a bout 1 degree which shows serious danger.

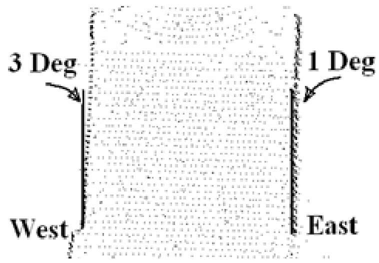

Figure 7: Inclination of Opposite Faces of the Prismatic Base Compared to the Vertical

The centers of two circular sections at the upper and lower ends of the trunk are out of alignment of more than 2.5 m as seen in figure 8a. The upper part of the trunk have a maximum tilt angle of about 9 degrees out of vertical towards east as seen in figure 8b.

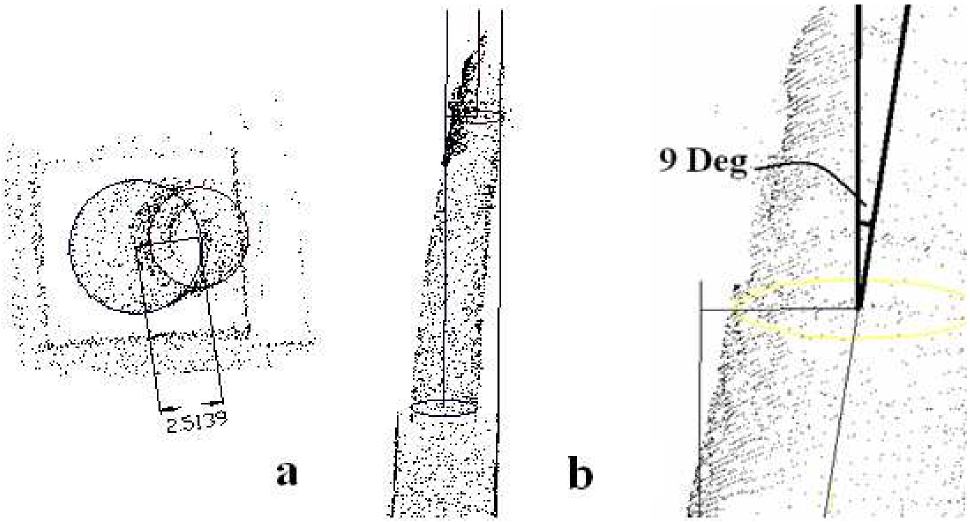

Figure 8: a) The Relative Eccentricity Between the Two Circular Sections at the Ends of the Trunk. b) Maximum Leaning Angle Out of Vertical at the Top.

Distance measurements were performed using the reflectorless mode from control point A to the targets on the facing side of the trunk of the minaret. Horizontal components of movements in mm of selected targets during two periods (from Oct. 2011 to Jan 2012 and from Jan 2012 to to May 2012) are shown graphically in figure 9. The Jan reading is used as a comparison reference in this case. During the first period, the measured leaning direction is to the East (towards control point A) with increased amount of leaning of 20 mm at upper elevations. The direction reversed during the second period with amount of 15 mm. The cause of this movement is attributed to one or more of possible causes such as irregular temperature variation, differential settlement, properties of building materials, humidity and wind effects etc. More sets of measurements were necessary to reveal the effect of each variable. The authors conclude that the upper part of the minaret has obvious movement that changes in magnitude and direction according to seasons.

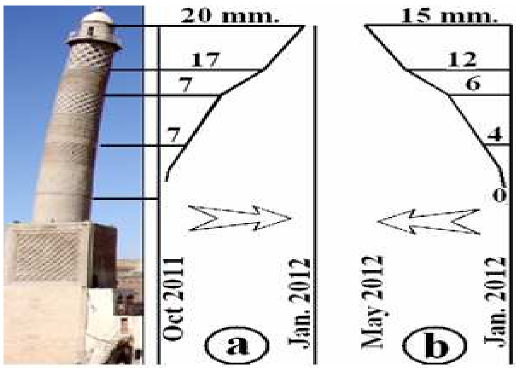

Figure 9: Horizontal Movements (Mm) of Targets in Two Periods, (Not To Scale) Before and After Jan-2012 a) Increased Leaning b) Reduced Leaning

PHOTOGRAMMETRIC MEASUREMENTS

Two sets of data have been compared to predict the history of amount of leaning using photogrammetric concepts. The first, an old rare photograph of the minaret probably dated back to year 1925 have been analyzed. The second set resembles a 3D representation of the minaret prepared using the scanning capability of the total station instrument. In order to make realistic comparison, care was taken to estimate the location of the shooting camera in order to orient the two data sets into the same alignment as much as possible. Figure 10 shows the overlay of the two sets and amount of leaning. From

this overlay, the authors expected that during the last 90 years, there was a considerable leaning movement of the upper points of the minaret that amounts to more than 2.5 m eastwards. The prismatic base overlay doesn't coincide well due to base tilt as shown earlier in figure 7. The authors argue that the major part of leaning of the minaret had occurred during the last century.

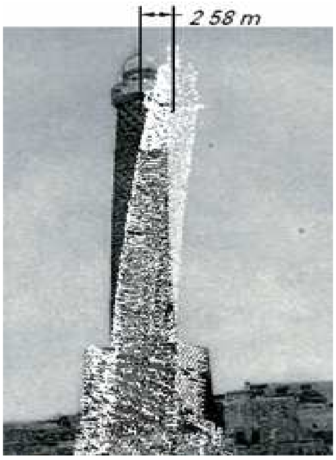

Figure 10: Estimated Leaning During the Last 90 Years

CONCLUSIONS

In this work, we have fixed permanent control points as well as permanent target points. Researchers could refer to this system for continuous monitoring of leaning and comparison. During the period of monitoring, we observed that a cyclic type of leaning exists. This is fluctuating around the year according to weather heat. We noticed the Maximum horizontal movement was observed at points in the upper part (kubba). The movement is less at lower elevations. The amount of eastward horizontal leaning in upper points increases in cold winter as compared to hot weather measurements. The probable effect of differential temperature on leaning is arguable and needs more research. Other probable causes of leaning are due to differential settlement of the base, wind effects, earthquakes and physical properties of the building material. We need more data collection and research to separate effects of these variables. Comparing with old photographs, the authors concluded that the most amount of (permanent) leaning in the minaret occurred during the last century. These findings will be beneficial to the efforts of rebuilding the minaret which is under preparation.

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